# Universal Laws of Disaster

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***Abstract*—Universal laws play fundamental roles in advancing science and technology. The literature on disasters is vast and multidisciplinary, but very little is quantitative and generally lacks rigorous theory and research on mathematical laws of disaster. This paper presents three formal classes of universal laws of disaster, based on the logic, probability, and severity of the phenomena. These laws are independent of specific drivers of disasters, such as natural or intentional (i.e., man-made) hazards. The main implication of these universal laws of disaster is they provide a core set of principles from which to develop a more viable, general theory of disasters. Such a theory would have pure and applied implications for the science, technology, and management of disasters.**

## I. Introduction[1]

### A. Motivation

Laws describe and theories explain. Modern science is replete with laws concerning many natural phenomena, some more universal than others. Boyle's universal law of gases, Newton's universal law of gravitational force, and Laplace's equation are among the best-known instances of mathematical laws in natural science, while Zipf's law of human regional settlements, Richardson's law of conflict severity, and the Weber-Fechner law of stimuli and perception come from domains of social and human sciences. Are there mathematical laws of disasters that are as universally and mathematically formulated?

Considering the value and powerful insights provided by universal laws across the natural and social sciences, it is clear that discovering comparable mathematical laws of disaster would be a valuable contribution to advancing theory and research, from a basic scientific perspective as well as from an applied technology and disaster management perspective. For example, having these laws would enable significant breakthroughs, such as gaining a deeper understanding of the causal structure of disasters, improving prediction or forecasting, and enabling disaster mitigation to lessen the impact of hazards on human communities experiencing disasters. Such gains would be valuable, considering that disasters have been a significant feature of human existence since the dawn of time. They occur daily worldwide and will continue in the future. Scientific laws of disaster can facilitate and enable technologies and policies to prevent or mitigate disasters.

A *disaster* $\mathbb{D}_\tau$ is an event that produces severe loss or damage of size $S$ in a given community at a given location $L$ at a given time $\tau$. The damage is multidimensional, containing human losses in terms of fatalities and injured, as well as economic, social, and sometimes political costs. In turn, disaster severity $S$ is one among several variables that define the state of a disaster as an $n$-tuple, other dimensions or variables being the time $\tau$ and location $(x, y)$ of occurrence, as well as the state of preparedness $P$, the intensity $I$ of the hazardous incident (such as the magnitude of an earthquake or the intensity of a flood), the vulnerability $V$ of the community affected by the disaster, and the effectiveness and cost of response operations $R$, among the most significant variables. Although many of these dimensions of disaster have known metrics or measurable proxies (e.g., the Richter-magnitude $\mu(\mathbb{D})$ of a seismic event), there has been little scientific research specifically focused on the formulation and testing of mathematical laws of disaster.

A significant challenge of disaster research is also one of its most scientifically intriguing characteristics: the multidisciplinary nature of disaster phenomenon, because the severity $S$ of a disaster $\mathbb{D}$ is a causal function of natural, engineering, and social or human variables. Accordingly, sufficiently complete mathematical models of disaster must draw from relevant disciplines from the natural, engineering, and social sciences. In the context of disasters, natural sciences include physics (seismology, meteorology, vulcanology, hydraulics, electricity and magnetism, among others, depending on the nature of the hazard involved), engineering (mechanical, civil, electric and electronic branches of engineering, depending on the built environment of the location affected), biology (at all levels, including organismic and population), and social science (anthropology, sociology, political science, among others). A specific disaster will narrow the disciplinary spectrum, but the general dynamics cover a broad range of disciplines and specializations, which explains the paucity of universal laws of disaster as complex events relative to laws of simpler phenomena. The challenge and overall requirement is to formulate a mathematical framework that is sufficiently general to gain scientific understanding, applicable to many disasters in space and time, while being able to apply the same universal laws to specific local cases or historical instances with sufficient

[1]Paper presented at the IEEE Global Humanitarian Technology Conference, Disaster Management Track, Seattle, Washington, USA, 13–16 October, 2016. This paper is dedicated to the memory of the late Italian architect and disaster planner Luciano Di Sopra, a pioneer in the application of mathematics and quantitative methods to disaster theory and management.

empirical detail and technical specification based on available or estimated case data.

### *B. Prior research on laws of disaster*

One of the most significant scientific accomplishments in 20th century disaster research was the conceptual distinction between a *hazard* event $\mathbb{H}$ and a *disaster* event $\mathbb{D}$ as separate albeit causally related categories (Quarantelli 1998; Mileti 1999; Stallings 2002; Perry & Quarantelli 2005; Rodriguez et al. 2007). A hazard $\mathbb{H}$ refers to the triggering incident event (e.g., hurricane Katrina), whereas a disaster $\mathbb{H}$ refers to all the effects of $\mathbb{H}$ on the human community affected (i.e., the severe losses inflicted on the population of New Orleans). The categorical distinction between a hazard $\mathbb{H}$ and a disaster $\mathbb{D}$ is nowadays accepted as fundamental and understood by the scientific community on disaster research and management. To wit, the 2005 New Orleans disaster (technically categorized as a *catastrophe*, as explained below) would not have occurred had the city not been in the path of hazardous hurricane Katrina. Similarly, the AD 79 catastrophic destruction of Pompeii, Italy, was a disaster caused by the eruption of Mount Vesuvius. Today, human settlements on the slope of the same volcano are another catastrophe waiting to happen.

Another significant accomplishment has been the development of various scales for measuring disasters, the most fundamental of which is the adoption by the scientific research and professional management community of what may be called the *ordinal scale of calamity*, based on resources needed to manage the response in a sufficiently satisfactory way (e.g., Quarantelli 1998; Rodríguez et al. 2007; Stallings 2002):

1) EMERGENCY: a loss incident where local response resources are entirely sufficient to manage the response. This is the lowest level of calamity. Examples include common and relatively simple and expected everyday occurrences, such as traffic accidents, house fires, or homicides, assuming only a few persons are involved. Most municipalities and local authorities within the incident's jurisdiction are normally equipped and professionally trained to deal with emergencies, with or without volunteer assistance.
2) DISASTER: a larger loss incident where local response resources are unable for whatever reason to manage the response in an effective way and resources in neighboring jurisdictions must be deployed in a coordinated way. This is the second level of calamity, greater than a mere emergency. Examples include uncommon or unexpected calamitous occurrences, such as massive road accidents (e.g., a large vehicular pile-up), complex multi-structure fires, or mass killings, when many persons and physical assets or critical infrastructure are involved. Managing a disaster requires close coordinated response among multiple jurisdictions.
3) CATASTROPHE: a major, large-scale incident in space and time where all available neighboring and even more distant response resources are insufficient to completely manage the response. This is the next-to-greatest level of calamity. Examples include extreme disaster events, such the 9/11 attacks (2001); Aceh, Indonesia (2004); New Orleans, United States (2005); Haiti (2010); and Fukushima, Japan (2011), among many others, some of them extending back centuries or millennia (e.g., the destruction of Damghan, Iran, by earthquake in AD 856, causing an estimated 200,000 fatalities; the Antonine plague of AD 165–180 in the Roman Empire, caused by smallpox or measles, causing an estimated 5 million deaths; the Minoan explosion of the Santorini volcano in Greece in 1645 BC; and numerous others on all continents).
4) EXTINCTION EVENT: the most severe or extreme loss incident is where no one may survive the hazard. This is the highest (and to this day still hypothetical) level of calamity. Examples include the extinction or near-extinction of our species by asteroid impact, super-volcanic eruption, drastic loss of biodiversity, global pandemic, sufficiently extensive bioterrorism, runaway climate change, total warfare, reversal of the earth's magnetic field, massive gamma-ray bursts from solar storms, uncontrolled self-perpetuating nanotechnology processes, and other global existential hazards (Tainter 1988; Reese 2003).

Unfortunately, in spite of its scientific, technological, and policy value, relatively few disaster researchers treat the calamity scale with the attention it deserves. What work has occurred on increasing the level of measurement from ordinal to higher precision (interval and ratio) is not covered here due to the main focus on laws of disasters. In the disaster management community the scale is known, especially by professional managers, but remains largely unknown or misunderstood among the broader disaster volunteer community.

More specifically on the topic of disaster laws, in the 1980s the late Italian architect and disaster researcher Luciano di Sopra (1984, 1986a, 1986b) published what may be arguably the first mathematical equation for the severity $S$ of a disaster as a function of the intensity $I$ of the causal hazard, the *ex ante* vulnerability $V$ of the community afflicted by the hazardous incident, and the extent of preventive measures $P$:

$$S = I\frac{V}{P}. \tag{1}$$

An English translation of di Sopra's (1986a) entire monograph in Italian, including charts and maps of the Friuli region affected by the 1976 magnitude 6.5 seismic event, was published as a companion volume (di Sopra 1986b) but somehow is not cited in the extensive English language literature.

Equation 1 is useful but has several shortcomings. First, it is incomplete, because it omits other significant causal variables such as response actions, and does not explicitly distinguish preparedness from mitigation as analytically and practically distinct aspects of prevention. Second, a minor omission but formal requirement is a proportionality constant to equate different measurement units. Finally, di Sopra's entire research effort seems to have been solely focused on damages caused by

Fig. 1. The late Italian architect and disaster researcher and planner, Luciano di Sopra [1926–2016] was, *inter alia*, a pioneer in the application of mathematical models for earthquake disasters. He was professor of urban studies at La Sapienza University of Rome, as well as emeritus at the universities of Florence and Naples, authored over thirty works in Italian and English, as well as the reconstruction plan for the region of Friuli, Italy, after the devastating 1976 earthquake. He was a leading figure in founding the Italian national agency for disaster management (Dipartimento della Protezione Civile), equivalent to FEMA, and was an international advisor in Mexico, San Salvador, Armenia, and Kazakhstan. Photo credit: Il Messaggero Veneto, edizione Udine, June 20, 2016.

earthquakes, without any attempt to generalize to other disaster modalities, including other forms of natural, engineering, and man-made disasters, or the causal logic of disasters as compound events. Nonetheless, di Sopra's equation marked a significant pioneering contribution to rigorous formal and empirical research on disaster phenomena.

On a less technical level than Di Sopra's early work, the American Red Cross (ARC 2016) has published the following equation on the size of a disaster:

$$\frac{(hazard + vulnerability)}{preparedness} = disaster, \tag{2}$$

where the equation somehow reverses (or perhaps confounds) causally dependent (disaster size $D$) and independent variables $(I, V, P)$. Another shortcoming of equation 2 is the failure to distinguish between preparedness $P$ and mitigation $M$ as categorically distinct modes of *ex ante* preventive measures. Whereas preparedness refers to preventive measures undertaken to respond effectively to hazards (e.g., having well-trained and equipped first responders), mitigation refers to preventive measures that lessen the impact of hazards on human lives, buildings, or the environment (e.g., enforcing strict building codes and zoning laws, or building shelters). Nonetheless, the ARC equation represents a step forward with respect to di Sopra's, because the class of hazards is nowadays accepted to include all modalities of hazards, including natural, engineering, and man-made disasters such as terrorism.

Surprisingly, an extensive search of the extant and vast literature on disaster theory and research failed to turn up other directly relevant equations. Most mathematical models of "disaster" in fact model aspects of hazards, primarily natural hazards, and their economic effects (e.g., Woo 1999; Okuyama & Chang 2004). By contrast, models of disaster focus on the drivers of human, economic, and environmental losses from the occurrence of various modalities of hazards.

## II. Laws of Disaster and Minimal Classes

The main purpose of laws of disaster is to obtain results that deepen our understanding of disasters and related calamities, beyond what is known from case studies and anecdotal evidence. Formal mathematical laws are also necessary for a viable theory of disasters, as are the distinctions and concepts of scale introduced earlier.

Disasters are complex phenomena with features such as: (i) spanning multiple causal domains (i.e., caused by natural, human, or artificial hazards), (ii) having multiple modes of occurrence (can occur through multiple paths independent of domain), and (iii) exhibiting multiple spatiotemporal scales (local nearest neighbors to global long-range interactions, tens of milliseconds to centuries or longer). Given such complexity, three classes of laws are minimally necessary to describe fundamental aspects of disasters, based on their causal logic, probability, and severity.

### A. *Causal logic laws of disaster*

The first category of disaster laws focuses on their causal logic, based on events $\{\mathbb{E}\}$, processes $\{\mathbb{C}\}$, and mechanisms $\{\mathbb{M}\}$, where $\mathbb{E} \subset \mathbb{C} \subseteq \mathbb{M}$, in increasing order of complexity. Given the categorical distinction between a hazard $\mathbb{H}$ and a disaster $\mathbb{D}$, each occurring at onset times $\tau$ and $\tau' \geq \tau$, respectively, we can write

$$\mathbb{D} \Rightarrow \mathbb{H}, \tag{3}$$

the reverse being false. Eq. 3 indicates that hazards are a necessary (albeit not sufficient) condition for disasters and may be viewed as a fundamental causal law of disasters.

Ontologically, a disaster $\mathbb{D}$ is a compound event caused by the conjunction of four necessary and sufficient conditions: (1) the onset of a hazard $\mathbb{H}$, (2) vulnerability $\mathbb{V}$ in the human community affected by $\mathbb{H}$, (3) lack or ineffectiveness of preparedness $\neg\mathbb{P}$, and (4) lack or ineffectiveness of response $\neg\mathbb{R}$, as shown in Figure 2. Formally, the first-order causality for the occurrence of $\mathbb{D}$ can be expressed as

$$\begin{aligned} \mathbb{D} &\Leftarrow \Psi_{\mathbb{D}}(\mathbb{H}, \mathbb{V}, \mathbb{P}, \mathbb{R}) && (4)\\ &= \mathbb{H} \wedge \mathbb{V} \wedge \neg\mathbb{P} \wedge \neg\mathbb{R} && (5)\\ &= \mathbb{H}\mathbb{V}(\neg\mathbb{P})(\neg\mathbb{R}), && (6) \end{aligned}$$

where $\Psi_{\mathbb{D}}$ is the indicator function of $\mathbb{D}$ and equation 5 is in standard Boolean form.

In turn, as shown in Figure 2, each of the four causal events that generate $\mathbb{D}$ can be expressed by its associated second-order

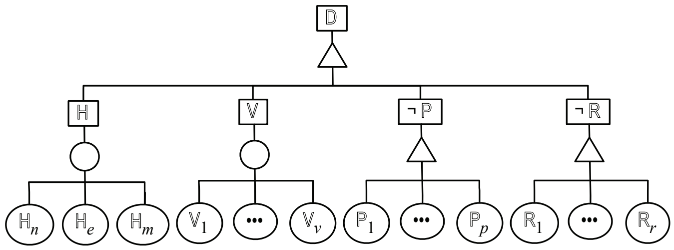


Fig. 2. Disaster event success tree with causal resolution of two levels. Notation: The top event $\mathbb{D}$ is the main event of interest (root event). Triangles and circles denote logic conjunction (Boolean AND) and disjunction (Boolean OR) operators, respectively. Bottom events in circles mark the limit of resolution of the tree at the second level of causation (leaf events).

equations for the indicator function $\Psi(\cdot)$, its event equation, and Boolean equation, respectively:

$$\begin{aligned}
\mathbb{H} &\Leftarrow \Psi_{\mathbb{H}}(\mathbb{H}_n, \mathbb{H}_e, \mathbb{H}_m) && (7)\\
&= \mathbb{H}_n \vee \mathbb{H}_e \vee \mathbb{H}_m && (8)\\
&= \mathbb{H}_n + \mathbb{H}_e + \mathbb{H}_m && (9)\\
\mathbb{V} &\Leftarrow \Psi_{\mathbb{V}}(\mathbb{V}_1, \cdots, \mathbb{V}_v) && (10)\\
&= \mathbb{V}_1 \vee \cdots \vee \mathbb{V}_v = \bigvee_{i=1}^{v} \mathbb{V}_i && (11)\\
\neg\mathbb{P} &\Leftarrow \Psi_{\mathbb{P}}(\mathbb{P}_1, \cdots, \mathbb{P}_p) && (12)\\
&= \neg\mathbb{P}_1 \wedge \cdots \wedge \neg\mathbb{P}_p = \bigwedge_{j=1}^{p} (\neg\mathbb{P}_j) && (13)\\
\neg\mathbb{R} &\Leftarrow \Psi_{\mathbb{R}}(\mathbb{R}_1, \cdots, \mathbb{R}_r) && (14)\\
&= \neg\mathbb{R}_1 \wedge \cdots \wedge \neg\mathbb{R}_r = \bigwedge_{k=1}^{r} (\neg\mathbb{R}_k). && (15)
\end{aligned}$$

Note that as already shown in Figure 2, $\mathbb{H}$ and $\mathbb{V}$ are caused by disjunction, because both can occur in multiple modes (natural, engineering, and man-made hazards, and multiple community vulnerabilities, respectively), whereas $\mathbb{P}$ and $\mathbb{R}$ occur by conjunction, because each requires multiple lower-level events (various requirements of preparedness and response, respectively).

In the case of hazards, it seems natural to specify eq. 9 at a third level of causation, based on multiple natural, engineering, and man-made hazards:

$$\begin{aligned}
\mathbb{H} &= (\bigvee_{all\ n} \mathbb{H}_n) \vee (\bigvee_{all\ e} \mathbb{H}_e) \vee (\bigvee_{all\ m} \mathbb{H}_m) && (16)\\
&= \sum_{all\ n} \mathbb{H}_n + \sum_{all\ e} \mathbb{H}_e + \sum_{all\ m} \mathbb{H}_m, && (17)
\end{aligned}$$

where the summations in eq. 17 are Boolean sums (inclusive ORs, meaning "and/or") over $n, e,$ and $m$ natural, engineering, and man-made hazard events, respectively.

Based on these second-order equations, the occurrence of disaster can be expressed in terms of more closely observable, second-order causal events:

$$\mathbb{D} = (\bigvee_{n,e,m} \mathbb{H}) \wedge (\bigvee_{all\ v} \mathbb{V}) \wedge (\bigwedge_{all\ p} \neg\mathbb{P}) \wedge (\bigwedge_{all\ r} \neg\mathbb{R}). \quad (18)$$

These event-based logic laws of disaster describe the causal occurrence of disaster phenomena in detail, with obvious intrinsic value. However, their level of detail can go several levels beyond what is demonstrated here by way of proof-of-concept. In addition, causal logic laws serve as a foundation for understanding other significant and insightful aspects of disaster, such as their probability and severity.

### *B. Probability laws of disaster*

Given the occurrence of a disaster $\mathbb{D}$, its probability $\Pr(\mathbb{D})$ is naturally interesting, because the occurrence of causal events in the indicator function $\Psi_{\mathbb{D}}$ (i.e., $\mathbb{H}, \mathbb{V}, \mathbb{P}, \mathbb{R}$) is uncertain:

- $\mathbb{H}$: onset, magnitude, location, duration, side effects, dependencies, and other attributes of hazards can be uncertain, unknown, or random.
- $\mathbb{V}$: the variety, extent, significance, and other attributes of vulnerability in the community affected can never be calculated with precision, and the real state of vulnerability may be impossible to assess.
- $\mathbb{P}$: preparedness measures must be identified, assessed, addressed by a plan, resourced, implemented, and maintained, amounting to a compound sequential and conjunctive event with significant cardinality and overall uncertainty.
- $\mathbb{R}$: similarly, post-disaster response measures typically involve complex and multiple requirements.

Based on the first-order event law of disaster (eq. 6), the *ex ante* probability of disaster affecting a community can be expressed as

$$\Pr(\mathbb{D}) = \Pr(\mathbb{H}) \cdot \Pr(\mathbb{V}) \cdot \Pr(\neg\mathbb{P}) \cdot \Pr(\neg\mathbb{R}). \quad (19)$$

Second- and high-order equations can be similarly derived, based on associated event-based causal logic laws presented in the previous section.

Equation 19 is precise but cumbersome to write and manipulate, especially when applied to higher orders beyond the first (e.g., eq. 18). Let $\mathcal{E}$ denote $\Pr(\mathbb{E})$, to simplify notation. Then, event equations 6 and 18 yield the following first- and second-order probability laws:

$$\begin{aligned}\mathcal{D} &= f(\mathcal{H},\mathcal{V},\mathcal{P},\mathcal{R}) \\ &= \mathcal{H}\mathcal{V}(1-\mathcal{P})(1-\mathcal{R}) \qquad (20) \\ &= g(\mathcal{H},\mathcal{V},\mathcal{P},\mathcal{R}; n,e,m,v,p,r) \\ &= \left[1-\prod_{h=n,e,m}(1-\mathcal{H}_h)\right]\cdot\left[1-\prod_{i=1}^{v}(1-\mathcal{V}_i)\right]\cdot \\ &\quad \cdot\left[\prod_{j=1}^{p}(1-\mathcal{P}_j)\right]\cdot\left[\prod_{k=1}^{r}(1-\mathcal{R}_k)\right], \qquad (21)\end{aligned}$$

where cardinalities in eq. 21 are specified for the four types of modalities associated with hazards $(n, e, m)$, vulnerabilities $(v)$, preparedness $(p)$, and responses $(r)$, respectively.

The first-order probability law of disasters (eq. 20) is a simple multiplicative function, as is common for compound events. (If $\mathcal{H}, \mathcal{V}, \mathcal{P}$, and $\mathcal{R}$ are not independent, then they require conditioning through additional functions for specifying each dependency.) Based on equation 20, under conditions of maximum uncertainty for each probability (highest entropy), when each of the four events is equiprobable (i.e., assuming $\mathcal{H} = \mathcal{V} = \mathcal{P} = \mathcal{R} = 0.5$), it follows that $\mathcal{D} = (0.5)^4 = 0.0625 \ll 0.5$, which is approximately one tenth the equiprobable value of 0.5. For all other nontrivial values (i.e., excluding 0 and 1), the function $f = \mathcal{X}^4$ yields values of $\mathcal{D} \ll \mathcal{X}$, a universal property of the probability of compound conjunctive events that may be called *hypoprobability*.

The second-order probability law of disasters (eq. 21) is more interesting because it reaches closer to observable features, such as the probability and cardinality of specific hazards, vulnerabilities, preparedness, and response measures. For example, assuming uniform probabilities across modalities, equation 21 yields

$$\begin{aligned}\mathcal{D} &= [1-(1-\mathcal{H})^3]\cdot[1-(1-\mathcal{V})^v]\cdot \\ &\quad \cdot(1-\mathcal{P})^p\cdot(1-\mathcal{R})^r, \qquad (22)\end{aligned}$$

which is more amenable to analysis. In turn, equation 22 can be reduced further by making additional simplifying assumptions, such as setting equal probabilities or equal cardinalities across the four independent variables.

### C. Severity laws of disaster

The severity $S$ of a disaster is defined as the aggregate loss caused by a disaster in terms of multiple dimensions, including human lives (dead or injured) and economic, social, political, and environmental losses or damages. In economic terms, disaster severity equates with a disaster's cost to individuals, groups, institutions (norms), or the environment.

Based on the causal logic law of disasters stated earlier (eq. 6), the severity $S$ of a disaster $\mathbb{D}$ is a function $\phi$ of the intensity $I$ of the hazard onset, the vulnerability $V$ of the community exposed to hazard $\mathbb{H}$, and preventive measures in terms of preparedness $P$, mitigation $M$, and response $R$. Specifically, $S$ is positively proportional to $I$ and $V$, and inversely proportional to the cumulative effect of preventive measures $P, M$, and $R$. Formally, the simplest specification of $\phi$ is given by the equation

$$\begin{aligned}S &= \phi(I,V,P,M,R) \\ &= k\frac{IV}{P+M+R}, \qquad (23)\end{aligned}$$

where all dependencies are assumed linear (simplest analytical case or baseline), so each exponent has value of 1, and $k$ is a proportionality constant to adjust for measurement units.

While equation 23 provides a viable first approximation, a more precise law should assign exponents to each independent variable, based on information from the partial derivatives of $\phi$. A more general law of disaster severity can be stated as

$$\begin{aligned}S &= \psi(I,V,P,M,R) \\ &= k\frac{I^aV^b}{P^c+M^d+R^e}, \qquad (24)\end{aligned}$$

where the exponents require estimation based on data. The next section discusses some aspects of these partial derivatives.

Empirically, $S(t)$ is a function of time $t$, where $t = \tau_0$ denotes the date of hazard onset. Hence,

$$S = \int_{\tau_0}^{\tau} S(t)dt. \qquad (25)$$

This concludes the presentation of the three classes of logic, probability, and severity laws of disaster. Additional classes would include distribution laws based on modeling dimensions of disaster as random variables (e.g, using a Poisson law to model the onset of hazards, or the Weibull distribution to model the severity of disasters, among others), as well as other forms based on different formal categories.

## III. Discussion

### A. On the universal laws of disaster

Based on the previous presentation it seems clear that several categories of formalisms exist that can be used to express universal laws of disaster phenomena in its many forms. The main equations presented here can be said to merely scratch the surface concerning the most salient disaster laws based on aspects of causal logic, probability, and severity of disasters. In addition, each of the laws presented is amenable to formal analysis, which is not only useful but necessary for generating additional results. Such analytical derivations can, in turn, be used to build a viable theory of disasters.

Empirical aspects are fundamental to any viable theory of disasters. But disaster data analysis without universal laws and theoretical principles is wasteful and potentially leads to erroneous inferences. Accordingly, universal laws of disaster such as those presented in this paper and others must be tested and calibrated with disaster data. Indeed, much more can be added to the laws included in this paper based on empirical observation. For example, the effect of hazard intensity (for hazards of various types) on disaster severity is likely to show a convex function $(0 < a < 1)$, rather than linear or concave. Similarly, preventive measures often show marginally decreasing effects on disaster mitigation, which should be reflected in the estimated exponents.

## B. Broader implications

The set of universal laws presented in this paper and elsewhere (Cioffi 2014) provides a viable basis for developing a general theory of disasters. Recall that laws describe and theories explain. In science, laws require explanation by theory. Such explanations enhance our understanding beyond what we gain by laws. Hence, while universal laws of disaster describe phenomena, a general theory of disasters is capable of explaining disasters by providing causal processes and mechanisms that account for the occurrence of disasters and calamities on various spatiotemporal scales.

In fact, the formulation of causal logic laws of disaster earlier in section II-A already alluded to processes and mechanisms. Further theoretical development would require specification of such processes and mechanisms, including specific details for various modalities of hazards (natural, engineering, and human), all under a common set of universal laws. A viable general theory of disasters would be composed of concepts and laws, such as the initial building blocks in this paper, and analytically and empirically demonstrable principles for explaining disasters with full scientific rigor.

## C. Future research directions

Three directions for future research stem directly from the class of universal laws reported in this paper. First, in order to go beyond mere face validity, strong empirical validation must be grounded on rigorous tests with real-world data using a carefully designed, representative sample of disaster cases. In order to support universality, such a sample must include a sufficient number of disaster cases of various types, intensities, locations, and other features that cover the full range of variation in this complex phenomenon. Moreover, given the ancient record of disaster in human history, such a validation sample must include cases from ancient epochs as well as recent time periods. If the universal laws of disaster are correct, they should hold across multiple scales of time, space, and social organizational complexity, from the smallest communities to the largest social systems (e.g., White 2011). Empirical applications and data-based tests must be a key component of the research agenda on universal laws of disaster.

Second, the computational methodology of agent-based modeling (ABM) is eminently suitable for advancing research on disasters and should be used for assessing, exploring, extending, and expanding the initial set of laws presented in this paper. For example, existing ABMs of coupled human-natural-artificial systems can be used to simulate the effects of various hazard modalities on human communities to see whether such effects obey universal laws. Interestingly, this is also a powerful methodology that has marked significant advances in recent decades across the engineering, social, and natural sciences, so agent-based computational models are also viable multidisciplinary integrators.

Third, the initial set of universal laws of disaster is ripe for extensive formal mathematical analysis. For example, sensitivity analysis and comparative statics are immediately applicable to probability and severity laws of disaster with significant potential for establishing new theorems and grow the general theory in a systematic way. Moreover, recent advances in the multivariate vector calculus of hybrid functions and fields using the so-called "nabladot" operator are also highly promising for gaining a deeper understanding of how such complex mathematical structures affect disasters (Cioffi 2014b, 2016).

Given the role of the built environment on disasters, all three research directions also jointly point toward the potential integration of multidisciplinary research on disasters and disaster management, based on engineering, biophysical, and social science knowledge.

# IV. Conclusions

Disaster research and management has evolved to the point where more systematic knowledge on disasters and related phenomena can now be encoded into formal laws and principles, such as those demonstrated in this paper. The starting point is arguably a conceptualization of disasters as being categorically distinct from hazards, a distinction already achieved during the latter part of the 20th century. In addition, from a scientific perspective, a disaster is an occurrence with associated (and measurable) variables, such as triggering hazard, geospatial location, severity, duration, and other attributes that characterize the occurrence.

The laws of disaster presented in this paper are universal in the sense that they apply independent of idiosyncratic hazard modes and other conditions. The severity of disasters, specifically, is increased by the intensity of hazards and by the level of a community's vulnerability, whereas it is decreased by the initial recognition of the hazard and by the quantity and quality of preventive measures (Cioffi 2014: 218219, fig. 7.6).

Universal laws of disaster are significant for research as well as for disaster management and applied aspects of disaster operations. Disaster managers may be familiar with aspects of the laws presented here, but having such laws formulated and analyzed in scientifically rigorous ways can provide useful insights and suggest ways of improving the use of resources in managing disasters. For example, the form of equation 22 guarantees that the probability of disaster is more sensitive to the probabilities associated with preventive measures than to the number (cardinality) of such measures: *better do a few things well, rather than many things poorly, hoping that some will work* is the right normative principle (although intuitively the two would seem equivalent—they are not). Each of the laws presented here holds practical significance—some clearly more than others—an aspect not detailed due to space limitations.

Given an initial set of universal laws, systematic scientific investigation using analytical, computational, and empirical methods can be used to develop a viable general theory of disasters. Such a theory is also critical for developing humanitarian technologies on more robust foundations and advancing the goals of disaster management and research.

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## APPENDIX I: LIST OF SYMBOLS

Symbols are listed in alphabetic order, starting with blackboard fonts (events), calligraphy fonts (probabilities), and italics (variables and values). Letters $i, j$, and $k$ are used as subscripts.

$\mathbb{D}$ disaster event
$\mathbb{C}$ generic causal process
$\mathbb{E}$ generic event
$e$ cardinality of engineering hazards
$\mathbb{H}$ hazard onset event
$\mathbb{H}_n$ natural disaster event
$\mathbb{H}_e$ engineering disaster event
$\mathbb{H}_m$ man-made disaster event
$\mathcal{H}$ probability of hazard onset event
$I$ intensity of hazard onset
$k$ proportionality constant
$\mathbb{M}$ generic causal mechanism
$M$ level of pre-hazard onset mitigation measures
$m$ cardinality of man-made hazards
$n$ cardinality of natural hazards
$\mathbb{P}$ pre-hazard onset preparedness measures
$P$ pre-hazard onset preparedness level
$p$ cardinality of preparedness measures
$\mathbb{R}$ response event
$R$ post-hazard onset response level
$r$ cardinality of response measures
$S$ severity of a disaster
$t$ analytical time
$\tau$ calendar time index
$\mathbb{V}$ occurrence of vulnerability in a community
$\mathcal{V}$ probability of vulnerability
$V$ vulnerability level of a community
$v$ cardinality of vulnerability modes
$\Omega$ sample space of events
$\Psi_{\mathbb{E}}$ indicator function for event $\mathbb{E}$

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